STRUCTURAL ANALYSIS CONSIDERATIONS FOR WIND TURBINE BLADES

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SUMMARY

Items which should be considered in the structural analysis of a proposed blade design are briefly reviewed. These items include the specifications, materials data, and the analysis of vibrations, loads, stresses, and failure modes. The review is limited to the general nature of the approaches used and results achieved.

INTRODUCTION

Wind turbine blades are being designed in a variety of configurations and are being manufactured from a variety of materials. It is the task of the structural analyst to verify that a particular design satisfies all requirements concerning structural integrity. These requirements include freedom from failure mechanisms such as fatigue, buckling, yielding and fracture, and limitations on deflection, wear, and corrosion. The purpose of this paper is to briefly review the items which should be considered when planning the structural analysis of a wind turbine blade. These items include specifications, materials data, and the analysis of vibrations, loads, stresses, and failure modes. Specialized methods for performing these analyses will not be discussed in this review, but rather the general nature of the approach and the results.

Among the many critical components in a wind turbine system, the blades are usually considered to be the most difficult to design. Typically, wind turbine blades are long flexible rotating airfoils which continuously sustain cyclic and transient loads. They must operate efficiently at off-design conditions because of the variability of wind speed and direction. As flexible airfoils, they are subject to aeroelastic and mechanical instabilities. However, the most difficult design requirements are those which are inherent in all wind energy systems. These are the requirements for all-weather operation, long service life, and low cost. In spite of these difficulties, reliable and economical wind turbine blades can be built, provided that the design is verified by structural analysis of the scope described in this paper.

For convenience, the activities of design and analysis are treated here as being separate and distinct. In reality, they are closely connected and iterative at the detail level. References 1 and 2 provide additional background information to illustrate this iterative process.

SPECIFICATIONS

Specifications are the set of requirements which do not change as iterations of structural design and analysis take place. In general, specifications restrict the designer and establish fixed allowable conditions or "criteria" for the analyst. Thus, blade specifications must be clearly defined and should be no broader in scope than is necessary to insure that the blade is compatible with the rest of the wind turbine system. The specifications of interest to the structural analyst can be grouped conveniently into the following five categories: (1) performance; (2) site; (3) geometry; (4) loading; and (5) reliability.

Performance specifications define requirements on rotor power, annual energy output, rotor speed, and wind speeds for cut-in, rated, and cut-out operations. Site specifications would include the annual average wind speed, the cumulative distribution of wind speeds during the year, the roughness of the terrain, wind turbulence, wind shear, the elevation of the site, temperature extremes, and the seismic zone. Further information on performance and site characteristics can be found in reference 3.

Geometry specifications establish requirements for compatibility between the blade and the other components of the wind turbine system. These specifications include requirements on the size of the blade, its aerodynamic profile, definition of interfaces such as hub connection, total blade weight, allowable ranges for blade natural frequencies, and allowable deflections.

Loading specifications define sets of operating conditions which constitute the required design load cases. Often, the structural analyst will add other cases which are found to be more severe. Tables I and II indicate the scope of design load cases currently defined for large horizontal-axis wind turbines. Table I lists the 21 load conditions and additional stability conditions defined for the 2.5 MW DOE/NASA Mod-2 wind turbine system now being designed by the Boeing Engineering and Construction Company (ref. 4). Table II presents the operating conditions for 10 load cases considered during the design of the 3.0 MW GROWIAN wind turbine currently being designed by the M.A.N. firm for the West German government.

Reliability specifications are closely connected with the loading specifications since they establish lifetimes and failure modes which must be considered for each load case. They also define other possible requirements such as lightning and corrosion protection and fail-safe design.

MATERIALS DATA

Documentation on the materials of construction is an important item which is shared by the structural designer and analyst.

This documentation generally includes the following information:

1. Selection criteria, the specific materials in the design.

2. Physical properties, such as specific gravity, thermal expansion coefficient, and corrosion resistance.

3. Mechanical properties, such as design allowable yield, ultimate, and fatigue stresses (S-N) curves, elastic moduli, ductility, and fracture toughness.

4. Quality assurance considerations such as procurement specifications, acceptance tests, process development tests, and inspection criteria.

Figure 1 illustrates documentation of fatigue allowable stresses by means of an S-N curve, in this case for a fiberglass/epoxy composite material. A curve-fit line through the test data is reduced in stress by one-third, to account for material variability and other degrading effects. The lettered points indicate calculated stresses for given load cases, which fall below the allowable lines, as required for a positive margin of safety.

Extra conservatism is required in establishing fatigue allowable stresses for blades if material deterioration by corrosion and fretting is possible. This is particularly true for wind turbine blades because of the requirement that they operate in an all-weather environment for many years while being subjected to continuous cyclic loading.

VIBRATION ANALYSIS

A vibration analysis is conducted to verify that the natural frequencies of the blade are within allowable ranges, to avoid amplification of periodic loads. In addition, mode shapes are defined for each natural frequency for later use in the calculation of aeroelastic loads. The scope of the vibration analysis should also include consideration of aerodynamic instabilities such as classical flutter and divergence.

Vibration mode analysis of structures like blades is usually conducted by means of finite element models and structural analysis computer codes like NASTRAN. The finite element model may be very detailed (ref. 6) if many modes are required or quite simple (ref. 7) if a few modes are sufficient. Results are presented as frequency tables (table 3, from ref. 6), Campbell diagrams (figure 2, from ref. 2), and normalized deflection shapes.

LOAD ANALYSIS

The objective of the load analysis is to define the forces and moments acting on cross-sections of the blade at stations

along its span. These forces and moments are technically "internal" loads which result from "external" load sources such as the wind, gravity, and inertia. Static, cyclic, and transient loads must all be calculated in order to evaluate the structural integrity of the blade. Critical static loads occur during extreme winds. Cyclic loading occurs continuously during wind turbine operation as a result of the effects of gravity and variations in wind speed across the rotor disk. Transient loads are usually critical during rapid shutdown of the machine.

Specialized computer codes are available to calculate both external and internal loads in wind turbine blades and in complete wind turbine systems (Ref. 8). Input to these cases includes blade mode shapes and natural frequencies (see VIBRATION ANALYSIS), chord and mass distributions along the blade span, airfoil lift and drag coefficients, rotor and wind speeds, blade twist and pitch angles, etc.

The load analysis is the key to determining whether or not a design meets the specified requirements. The load analysis approach should be well documented, including the load cases to be analyzed, the computer codes to be used, supporting information such as sign conventions and nomenclature, and limitations of restrictions. The load analysis is often conducted on an idealized model of the blade, and this model must be documented as well.

Figures 3 and 4 show typical results of blade load analysis. Figure 3 (Ref. 2) shows a typical spanwise distribution of maximum and minimum flatwise (out-of-plane) bending moments which occur during each rotor revolution at rated conditions. These loads are the basis of a subsequent fatigue endurance analysis for this operating condition. Figures 4 (a) and (b) (Ref. 9) show typical variations in cyclic flatwise and edgewise (in-plane) moment loads near a blade root, as the wind speed varies. Cyclic moment is defined as one-half the difference between the maximum and minimum moments during one rotor revolution. The predicted lines in Figures 4 (a) and (b) are for levels of load designated as "mean $+1\sigma$", which means that approximately 84 percent of the rotor revolutions at a given wind speed are expected to exhibit cyclic loads smaller than the prediction and 16 percent would be larger. Consideration of the statistical variation in blade loads is required either in each load analysis or in the subsequent stress analysis.

STRESS ANALYSIS

After loads have been defined at selected blade cross-sections for each required load case, local stresses can be calculated by conventional methods. The simplest of these methods considers the blade to be a beam. This is usually sufficient for the calculation of spanwise stresses in the surface elements of the blade away from

discontinuities. Blades with internal webs and spars are treated as multi-cell airplane wings (Ref. 10) when shear stresses are important.

For increased accuracy, finite-element models of the NASTRAN type are used for the analysis of stress, particularly at critical joints. Figure 5 (Ref. 2) illustrates the complexity of a finite-element model of a blade root. Because of this complexity and the accompanying expense, finite-element modeling is usually restricted to critical segments of the blade, in order to calculate joint stresses or to verify buckling margins, for example.

Because of the requirement that wind turbine blades must function under cyclic loading in an all-weather environment for many years, special attention must be given to so-called "secondary" stresses. These are the stresses caused by discontinuities in cross-sections, transverse loads from spars and ribs, fit-up loads, etc. These stresses can contribute to fatigue failures and must be considered as primary, not secondary.

Documentation of the stress analysis procedures should include descriptions of the critical sections to be analyzed, the computer codes used, cross-sectional dimensions and properties, and appropriate stress concentration factors which account for fasteners and other discontinuities.

FAILURE MODE ANALYSIS

Failure mode analysis is the final step in judging the structural integrity of a wind turbine blade or of any structural component. Failure modes which must be considered include fatigue, buckling, yielding, fracture, deflection, and wear. Theoretically, the analyst can determine margins of safety by simply comparing calculated stresses with design allowable stresses (see MATERIALS DATA). In reality, engineering judgment is required because of such factors as the statistical nature of the blade loads, approximations in the stress analysis, and allowances for environmental effects, unless the latter have been included in the design allowable stresses.

Upon completion of the failure mode analysis, margins of safety are documented for all sections of the blade, with respect to each failure mode. Figure 6 illustrates this documentation for the Mod-2 blade (Ref. 4). The structural analyst then judges whether or not the requirements of the specifications have been satisfied and discusses deficiencies, if any. Finally, recommendations are made concerning any design changes or operational limits.

CONCLUDING REMARKS

The design and analysis of wind turbine blades is still in a state of development. Nevertheless, valid judgments as to the

structural integrity of a proposed blade will continue to depend on careful consideration of the factors described briefly herein: the specifications, materials data, vibrations, loads, stresses, and failure modes. In general, the structural integrity of a wind turbine blade is judged by the same methods which are used for many other structures. However, the difficult requirements of all-weather operation and very long life under continuous cycling demand that special consideration be given to secondary stresses, and that extra conservatism be used in setting fatigue allowable stresses.

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DISCUSSION

Q. There was much talk about all the available tools, but no discussion of the most difficult part of the analysis, the fatigue environment over the life of the machine. What are your thoughts on that?

A. As you may recall, in the S-N curve that was shown, there were some words about spectra. The machine does not see just one cyclic load through its life which gives rise to cyclic stresses of a certain amplitude. It sees a wide variety of load cycles, and generally what is done is to categorize those cycles as to their size and the number of times they occur. This then becomes the load spectrum.

We do not yet have measured load spectrum for wind turbines, as you might expect would exist for a bomber wing or a fighter aircraft tail section. Also, we don't as yet have extensive "flight" spectra. Such data will be obtained from the Mod-OA and Mod-1 tests. However, it is necessary to account for not only the normal operating conditions, but for all of the abnormal operating conditions that make up this spectrum.

Q. The cyclic loading is basically a statistical process. If it is measured on the Mod-0, that doesn't indicate what will happen to another machine. A better feel may be obtained, but you won't know for sure. Don't you have to approach the problem in a statistical sense?

A. Yes. We are doing that in any load calculation. Some type of a probability of that load occurrence must be assigned. On one of the diagrams which was shown, the calculated loads were assumed to be the mean load plus one sigma, or one standard deviation. That is, 84 percent of the cycles at that particular condition of wind would be expected to fall below that load level. That will probably vary from machine to machine.

Our experience can help with certain items. For example, the number of times the machine is started and stopped can be estimated. This is a very significant load cycle. Also, the response of the Mod-OA machines to gusts tells us how often gusts of various sizes will occur.

Q. Did the failure of the Mod-0 blade occur on the upper or lower surfaces or on both surfaces?

A. The cracks which did occur in the root area were first seen on the low pressure side of the blade, which would be the upper side. The blade is highly twisted, so that is why it is hard to answer that precisely. However, cracks generally occurred on the low pressure side of the blade first.

TABLE I. - LOAD AND STABILITY CONDITIONS FOR THE 2.5 MW MOD-2 WIND TURBINE SYSTEM (REF. 4).

Function		Environment							
		Normal (-40° $120^{\circ}F$)	Gust	Extreme wind	Ice	Snow	Hail	Projectile impact	Seismic
Normal Operating	Startup	1							
	Operating	2	3				4	5	6
	Shutdown	7							
	Parked			8	9	10	11	12	13
Operating Fault	Loss of electrical load	14							
	Control sys. malfunction (1.5 x rated power)		15						
	One tip jammed	16							
	One tip control lost	17							
	Inadvertent braking	18							
Transportation and Handling	Shipping	19							
	Handling	20							
	Erection	21							
Stability	Classical blade flutter & divergence Stall flutter Rotor/generator Tower vortex shedding				Flap/lag/torsion Rotor/tower Pitch control feedback Yaw drive control				

TABLE II

SUMMARY OF DESIGN LOAD CONDITIONS FOR THE WEST GERMAN GROWIAN WIND TURBINE

Load Case No.	Design Condition	Wind speed		Rotor speed / Rated speed	Blade pitch	Fatigue life, cycles
		Steady	Gust / Steady			
(a) Cyclic Load Cases (fatigue stress allowables; 1.2 safety factor)						
1	Steady operation	spectrum	0	1.00	variable	$5x10^8$
2	Upgust	rated	1.00	1.00	fixed	10^4
3	Downgust	cut-out	-0.40	1.15	fixed	10^4
4	Upgust	cut-out	0.60	1.15	fixed	50
5	Upgust	cut-out	0.60	0.85	fixed	50
6	Downgust	1.2 x cut-out	-0.33	1.15	fixed	50
7	Emergency stop	1.2 x cut-out	0	1.15	max rate	500
(b) Limit Load Cases (breaking stress allowables; 1.5 safety factor)						
8	Extreme wind (broadside)	60 m/s	0	0	-90 deg	--
9	Extreme wind (idling)	60 m/s	0	0.20	variable	--
10	Maintenance	46 m/s	0	0	0 deg	--

TABLE III.- CALCULATED NATURAL FREQUENCIES OF THE 100 KW MOD-0 WIND TURBINE SYSTEM. (REF. 6).

MODE NO.	DESCRIPTION	FREQ (Hz)	FREQ (1/REV)
1	ROTOR ROTATION	0.39	0.67
2	1ST ROTOR FLATWISE-CYCLIC	1.42	2.44
3	1ST ROTOR FLATWISE-COLLECTIVE	1.52	2.60
4	TOWER BENDING-Y AXIS	1.81	3.10
5	TOWER BENDING-Z AXIS	1.91	3.28
6	1ST ROTOR EDGEWISE-CYCLIC	2.43	4.16
7	2ND ROTOR FLATWISE-CYCLIC	3.28	5.63
8	2ND ROTOR FLATWISE-COLLECTIVE	3.64	6.25
9	SHAFT TORSION	4.00	6.86
10	TOWER TORSION	4.18	7.16
11	3RD ROTOR FLATWISE-CYCLIC	6.41	10.99
12	3RD ROTOR FLATWISE-COLLECTIVE	6.62	11.35
13	BLADE TORSION-ANTISYMMETRIC	6.76	11.60
14	BLADE TORSION-SYMMETRIC	6.78	11.63
15	2ND ROTOR EDGEWISE COLLECTIVE	7.54	12.92
16	TOWER 2ND BENDING ~ Z AXIS	8.37	14.35
17	TOWER 2ND BENDING ~ Y AXIS	8.70	14.91
18	2ND ROTOR EDGEWISE - CYCLIC	9.10	15.59

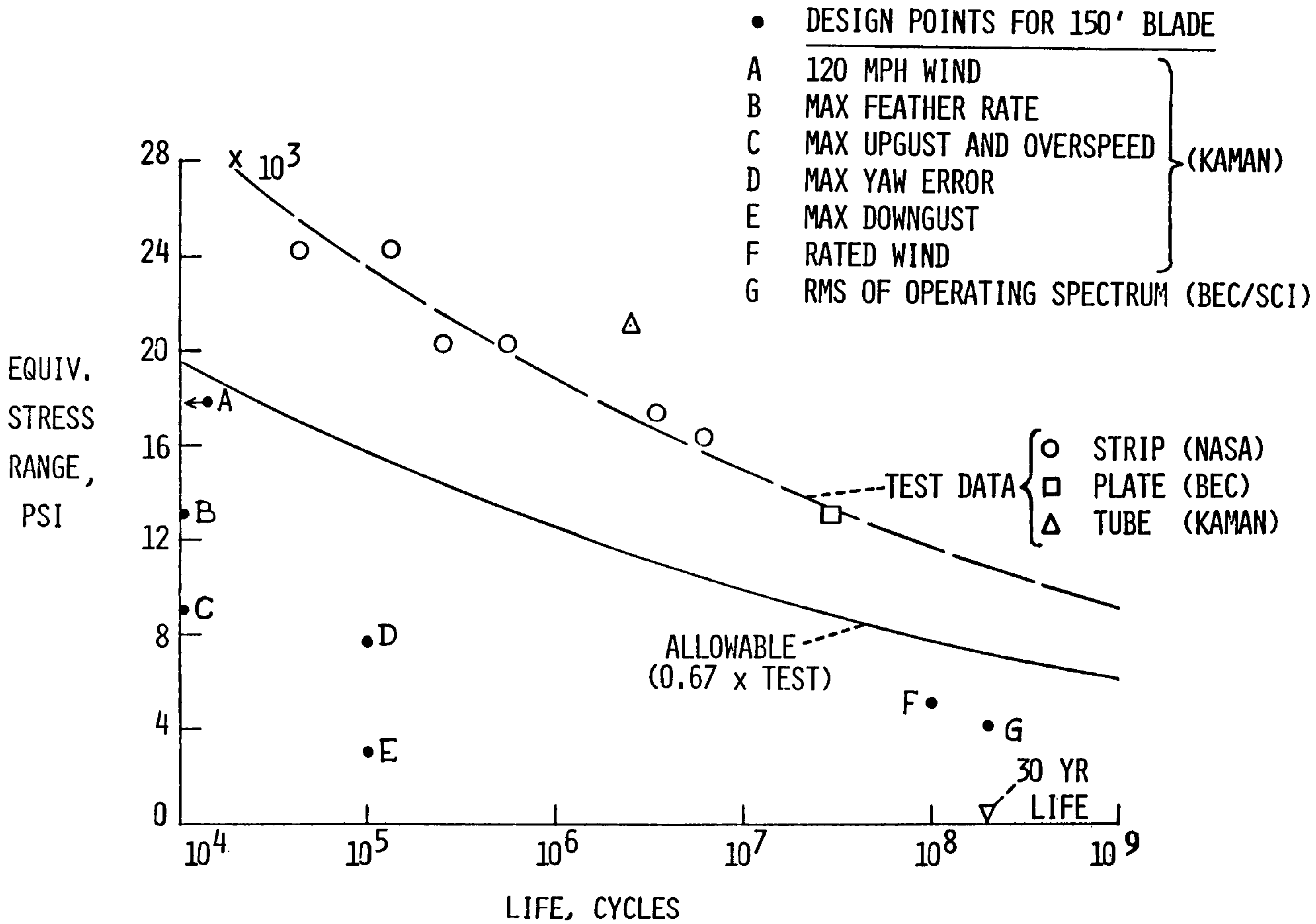


FIGURE 1. - FATIGUE DATA FOR FIBERGLASS/EPOXY COMPOSITE MATERIAL (TFT).

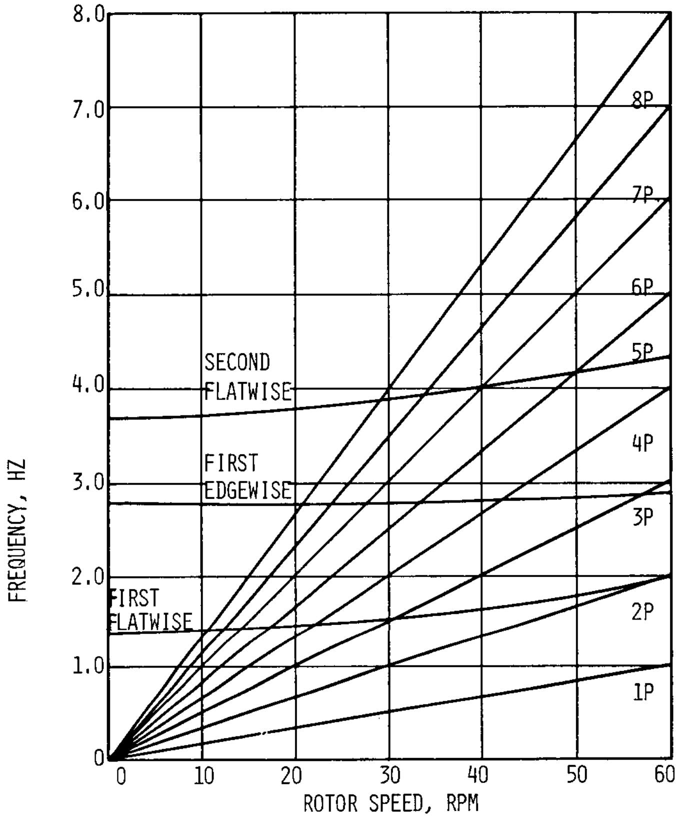


FIGURE 2. - CAMPBELL DIAGRAM OF UNCOUPLED FREQUENCIES FOR 62.5 FT. COMPOSITE WIND TURBINE BLADE. (REF. 2).

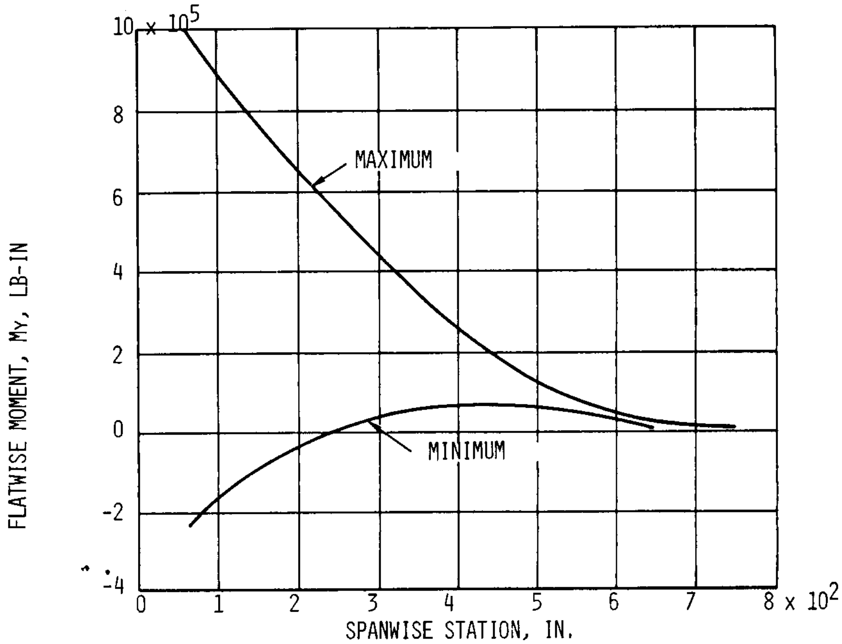
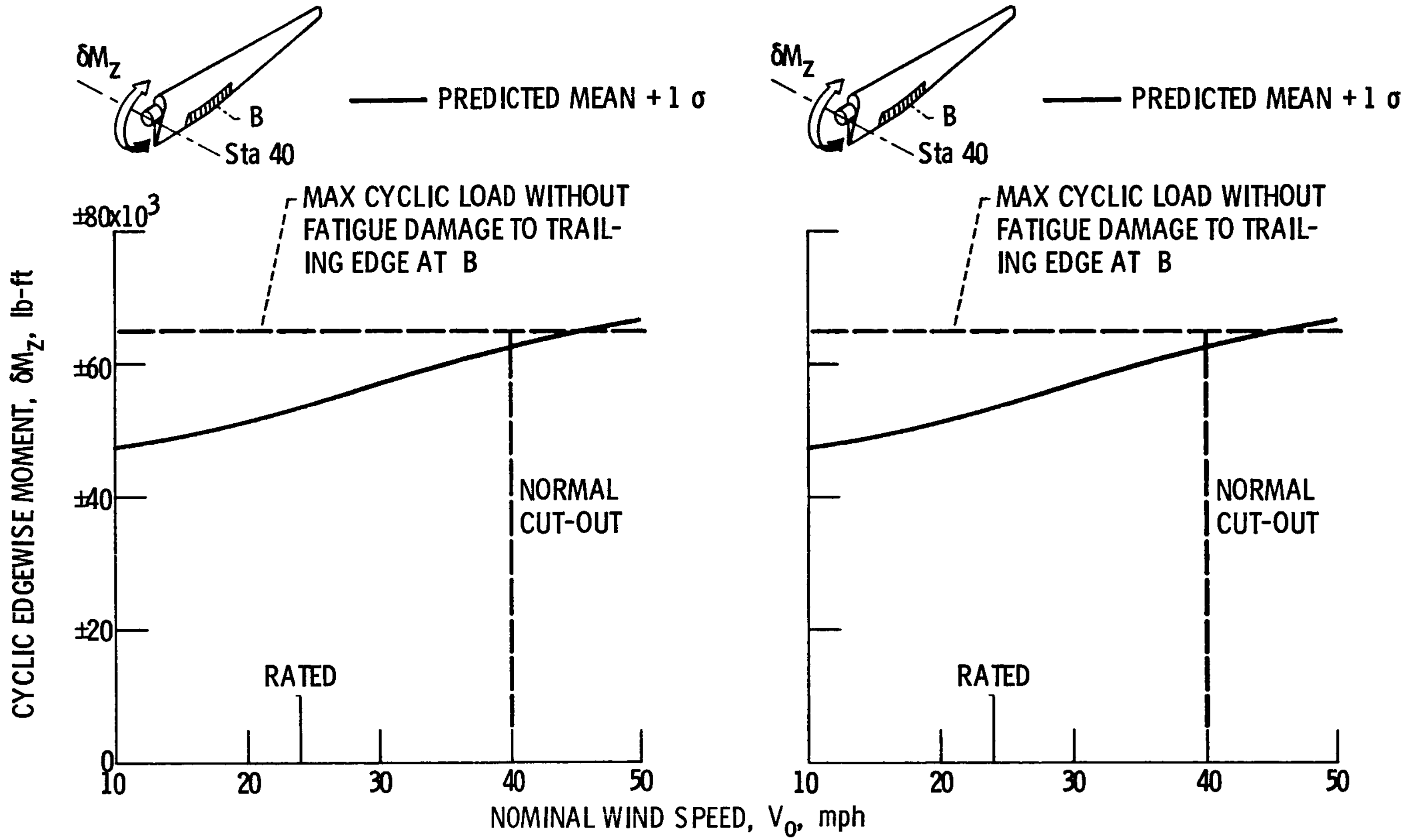


FIGURE 3. - CALCULATED FLATWISE MOMENT DISTRIBUTION IN 62.5 FT. COMPOSITE WIND TURBINE BLADE - LOAD CASE 1. (REF. 2).



(a) Flatwise bending.

(b) Edgewise bending.

FIGURE 4. - PREDICTED CYCLIC FLATWISE AND EDGEWISE BENDING LOADS FOR MOD-OA 200 KW WIND TURBINE BLADES.

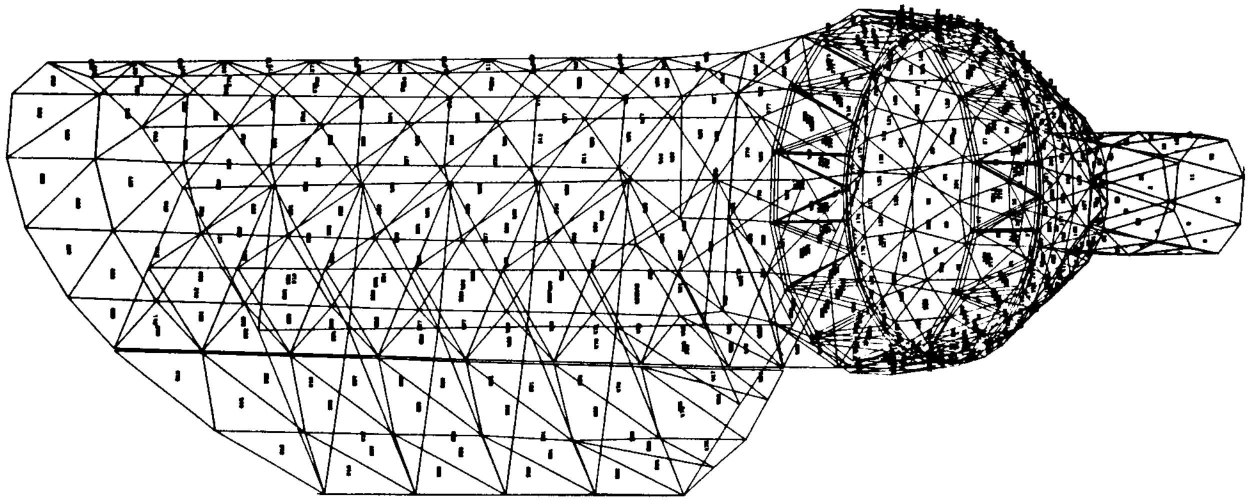


FIGURE 5. - FINITE ELEMENT MODEL OF ROOT SECTION OF 62.5 FT. COMPOSITE WIND TURBINE BLADE. (REF. 2).

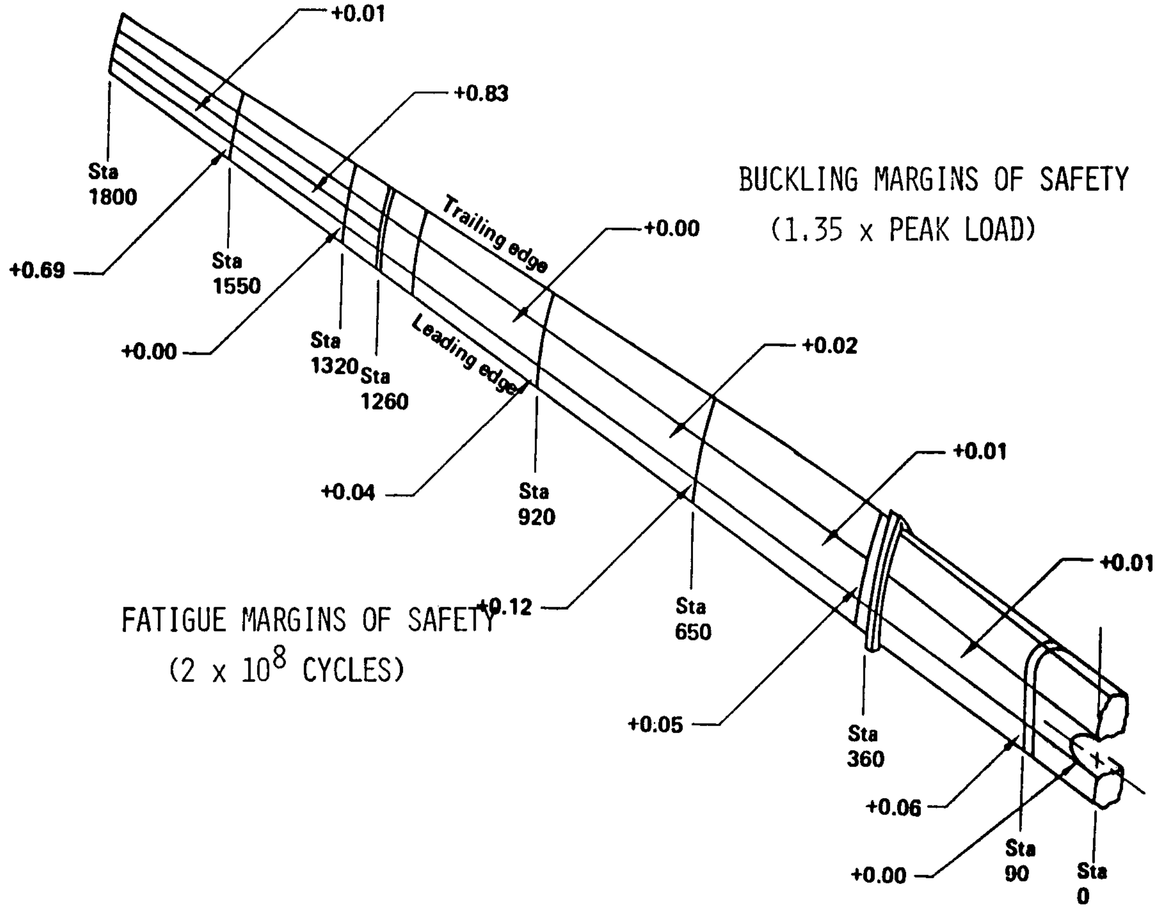


FIGURE 6. - ROTOR BLADE SKIN GAGES - MARGINS OF SAFETY FOR THE 2.5 MW MOD-2 WIND TURBINE SYSTEM. (REF. 4).